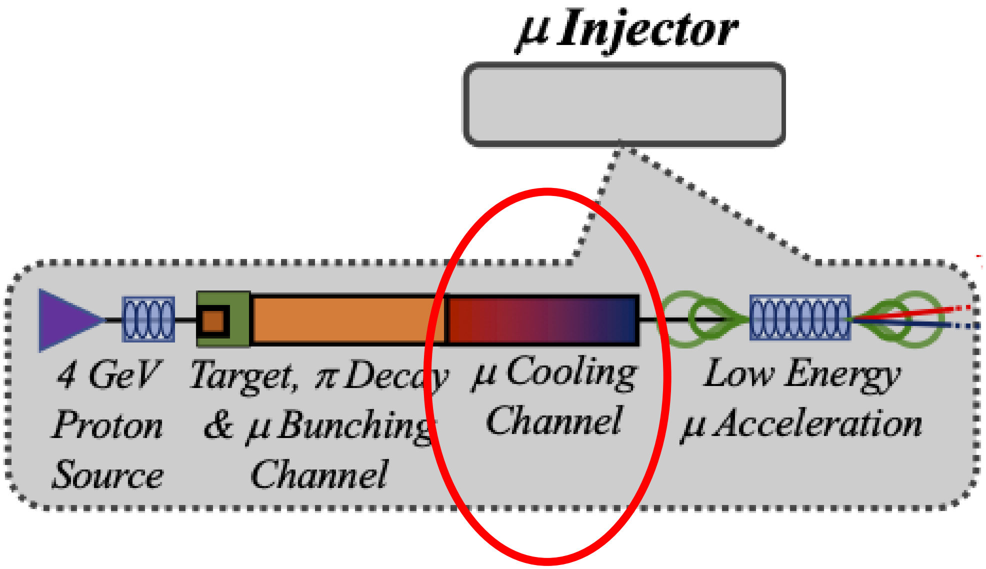
Prospects of Cryo-Cu and HTS high gradient RF cavities

Sergio Calatroni – CERN
With contributions from many Collaborators

Motivation

- Muon cooling system requires RF cavities operating at high-gradient AND in a strong magnetic field.



- Normal conducting copper, possibly cryo: see next talks
- Superconducting: High-Temperature Superconductors (HTS) ?

Outline

- HTS cavities in a strong magnetic field
- HTS cavities at high-gradient
- HTS cavities in both strong field and high-gradient
- Future steps

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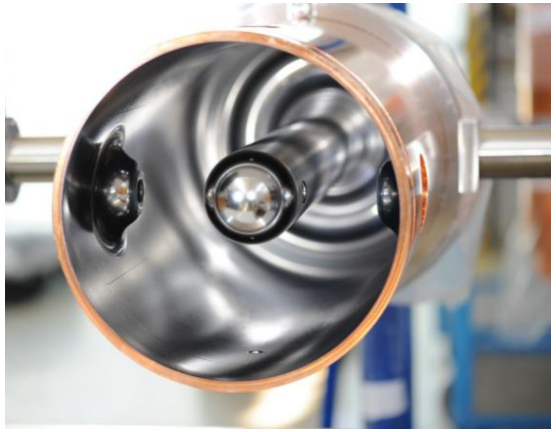
Reference case

- Typical SRF accelerator cavities are made of niobium

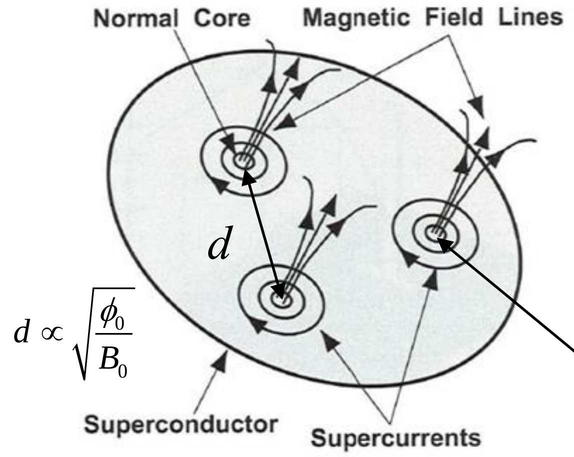
Strong magnetic shielding needed



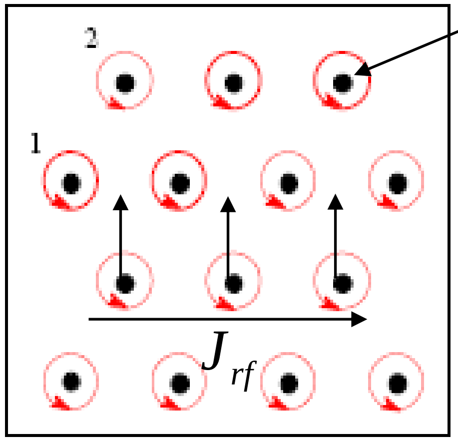
Limited or no magnetic shielding

- Effect of external magnetic field on SRF accelerating cavities is mostly due to flux pinning, weak pinning in bulk Nb and strong in Nb/Cu
- Niobium critical field $H_{c2} < 1$ T, superconductivity is lost at higher fields

Some theory background: fluxon motion in RF



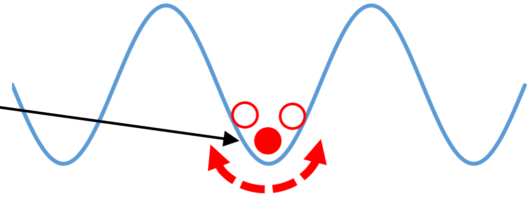
Pinning centers



B field is normal to surface: worst case

The motion of the rigid fluxon lattice behaves as a harmonic damped oscillator (neglecting thermal creep)

$$\boxed{m\ddot{x} + \eta\dot{x} + kx = J_{rf}\phi_O}$$



$$\eta = \frac{\phi_o B_{c2}}{\rho_n} \qquad k = \frac{2\pi J_c \phi_0}{d} \qquad \omega_o = \frac{k}{\eta}$$

The “depinning frequency”

$$\boxed{f_o(B_o) = \frac{\omega_o(B_o)}{2\pi} = \frac{\rho_n\sqrt{B_o}\,J_c(B_o)}{\sqrt{\varphi_o}\,B_{c2}}}$$

Surface resistance

$$\boxed{R_f = \frac{\rho_n}{2\lambda}\,\frac{B_o}{B_{c2}}\,\frac{f^2}{f_0^2}}$$

Gittleman and Rosenblum: Phys Rev. Lett. 16, 734 (1966)
Calatroni and Vaglio, IEEE Trans. Appl. Supercond. 27 (2017) 3500506
Coffey, Clem PRL 67, 386 (1991)
Brandt PRL 67 2219 (1991)
Silva et al, PRB 78, 094503 (2008)

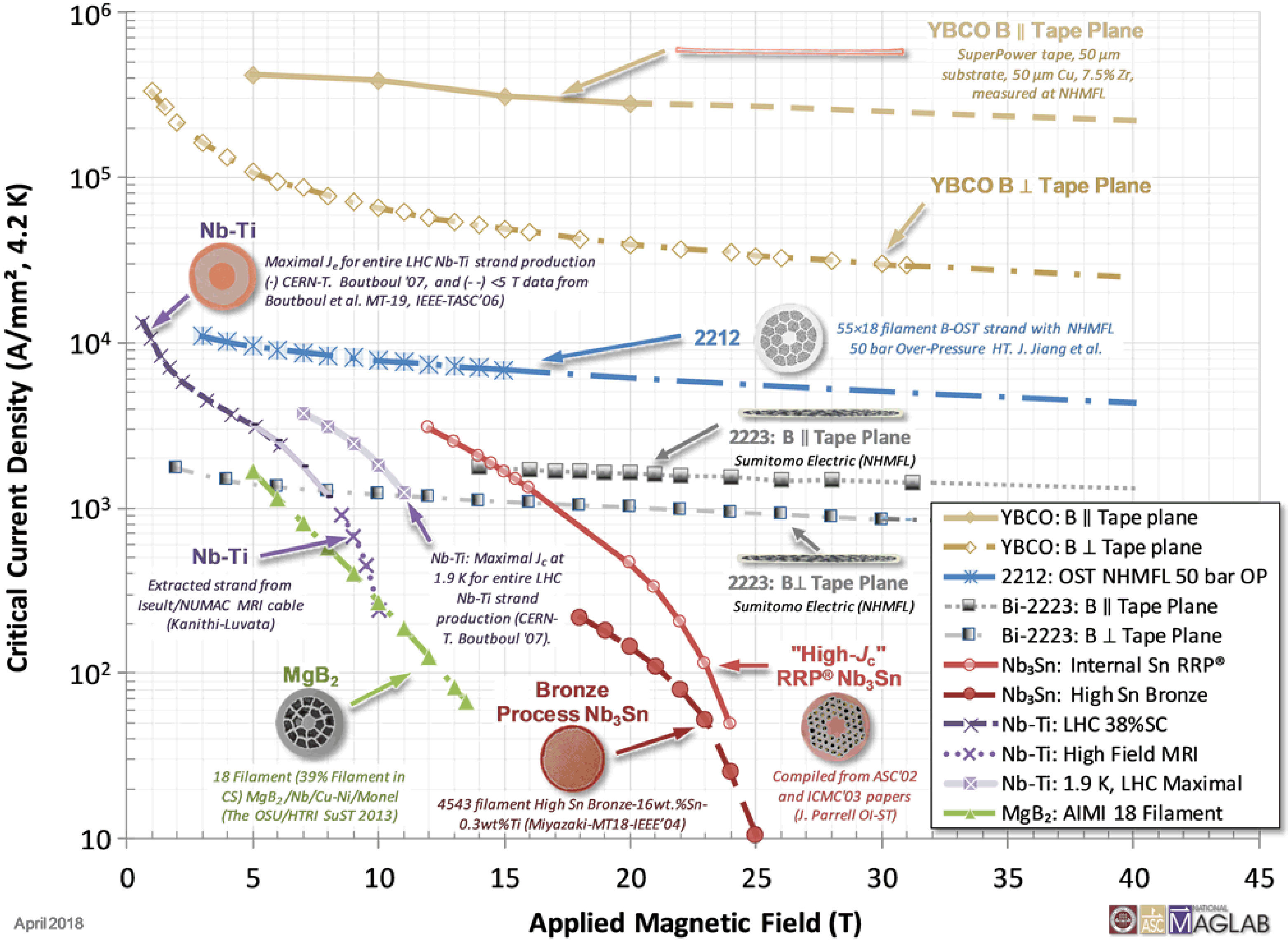
Zoo of superconductors

J_c may vary of orders of magnitude.
H_{c2} has much smaller variation.

YBCO most promising candidate

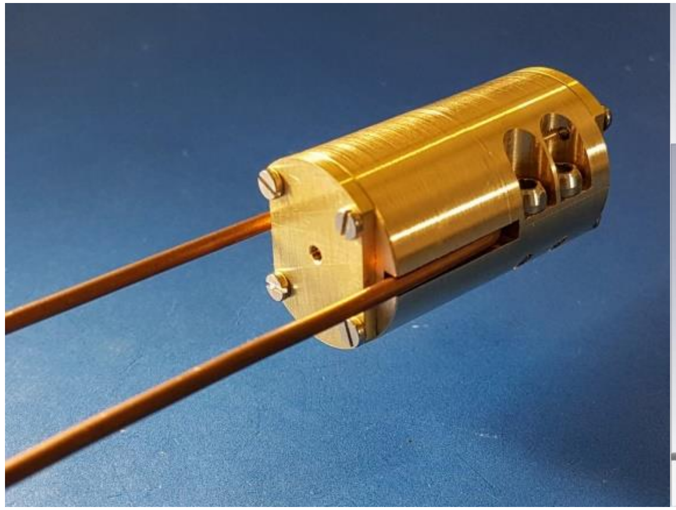
NbTi – NbTiN possible candidates at B < 10T

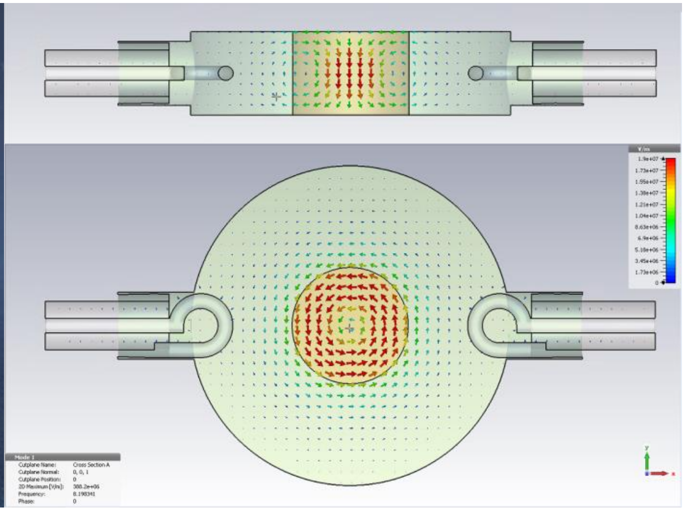
Nb_3Sn for B < 15 T



https://nationalmaglab.org/magnet-development/applied-superconductivity-center/plots

Validation of RF performance (UPC - ICMAB)





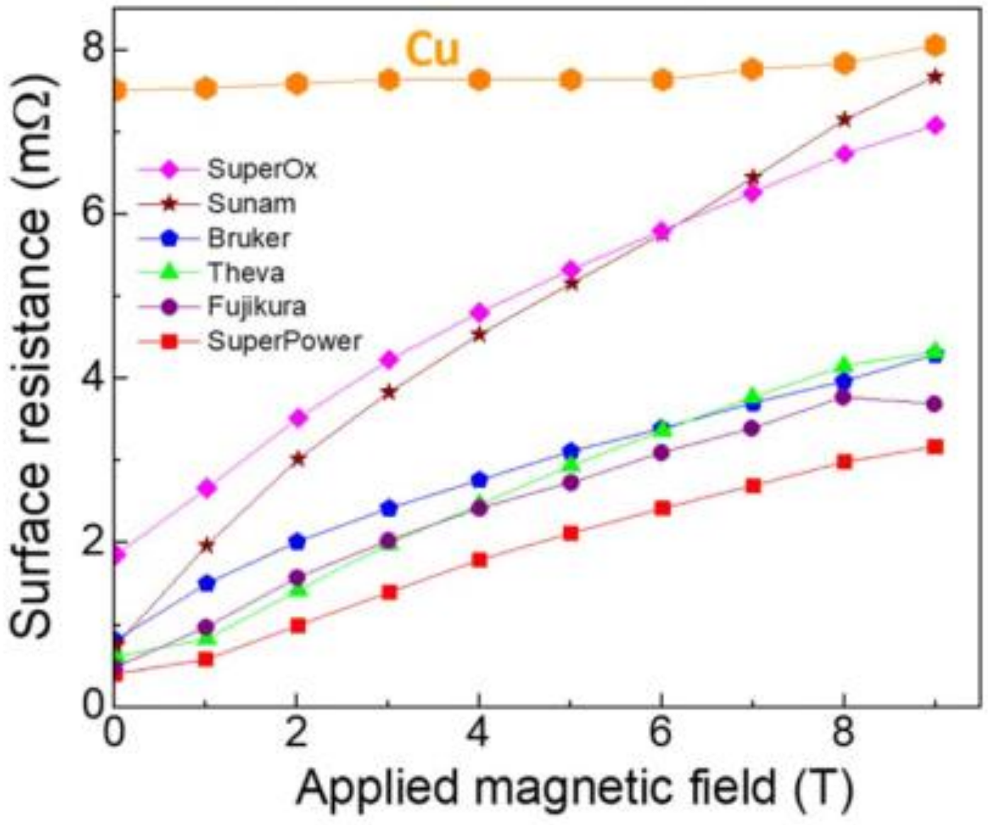


Figure 3. Magnetic field dependence of the surface resistance at 8 GHz and 50 K. Up to 9 T, CCs' R_s outperforms that of copper.

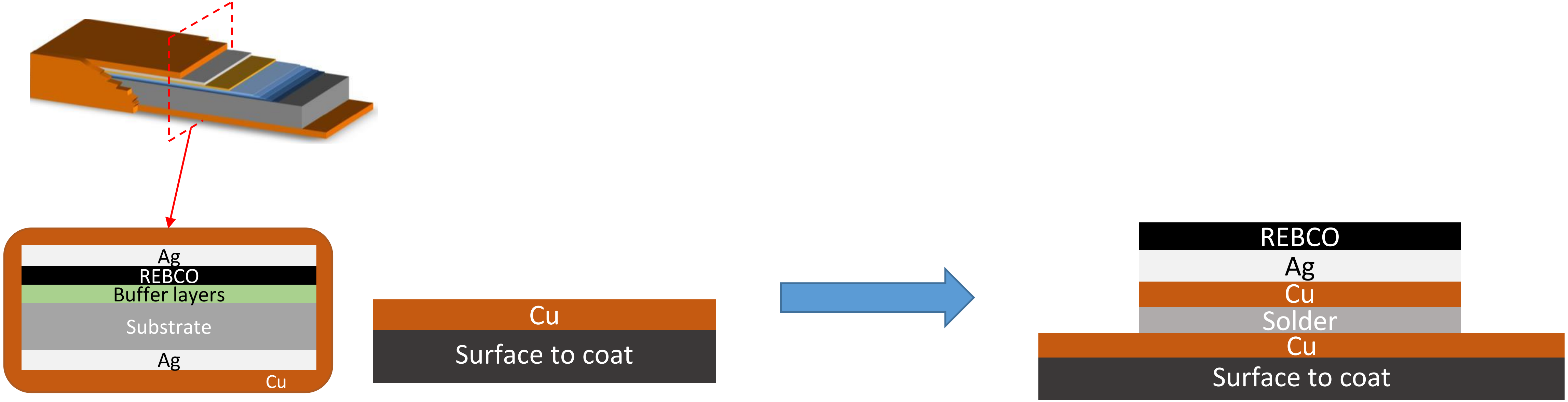
In house developed 8.05 GHz cavity resonator compatible with 25mm bore 9 T magnet at ICMAB

REBCO CCs outperform Cu at 50K and up to 9T
R_S is microstructure dependent

Puig et al, SuST 32, 094006 (2019)

Surface currents equivalent to 0.1 MV/m of a typical accelerating cavity

HTS coated conductor soldering and delamination



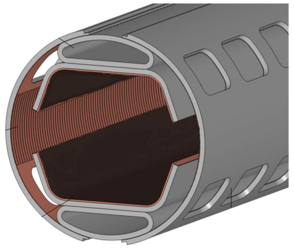
Ag
REBCO
Buffer layers
Substrate
Ag
Cu

Cu
Surface to coat

REBCO
Ag
Cu
Solder
Cu
Surface to coat

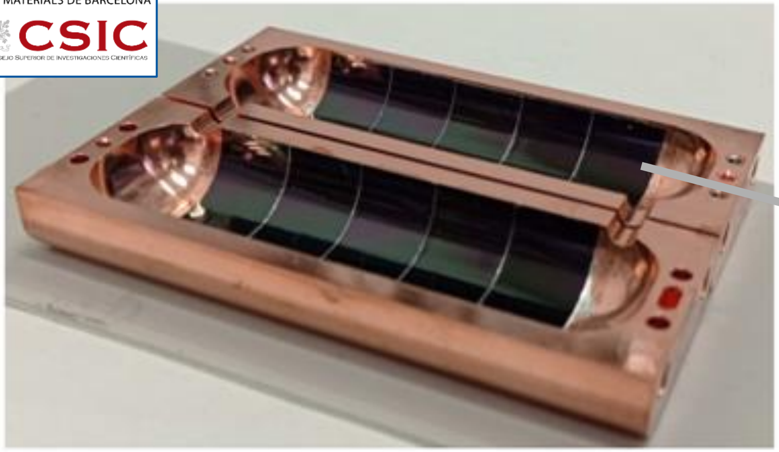
N. Lamas et al., to be published

Developed in the context of FCC-hh impedance reduction by coating the beam screen with HTS tapes

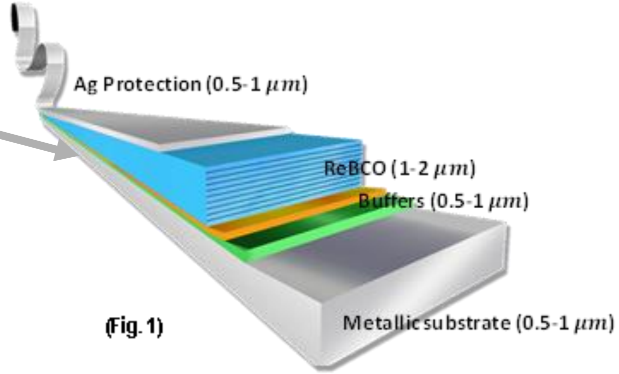


First real cavity, f≈9 GHz

- We have developed a technology for applying 2D HTS tapes to 3D RF "RADES" cavities demonstrating the potential of HTS for RF applications J. Golm et al., IEEE TAS, Vol. 32, No. 4, (2022) 1500605



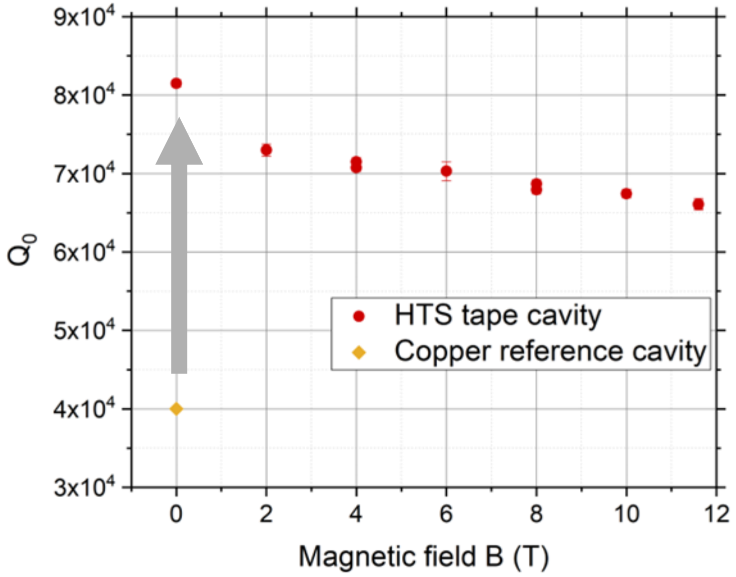
12 mm-wide HTS tapes



(Fig. 1)

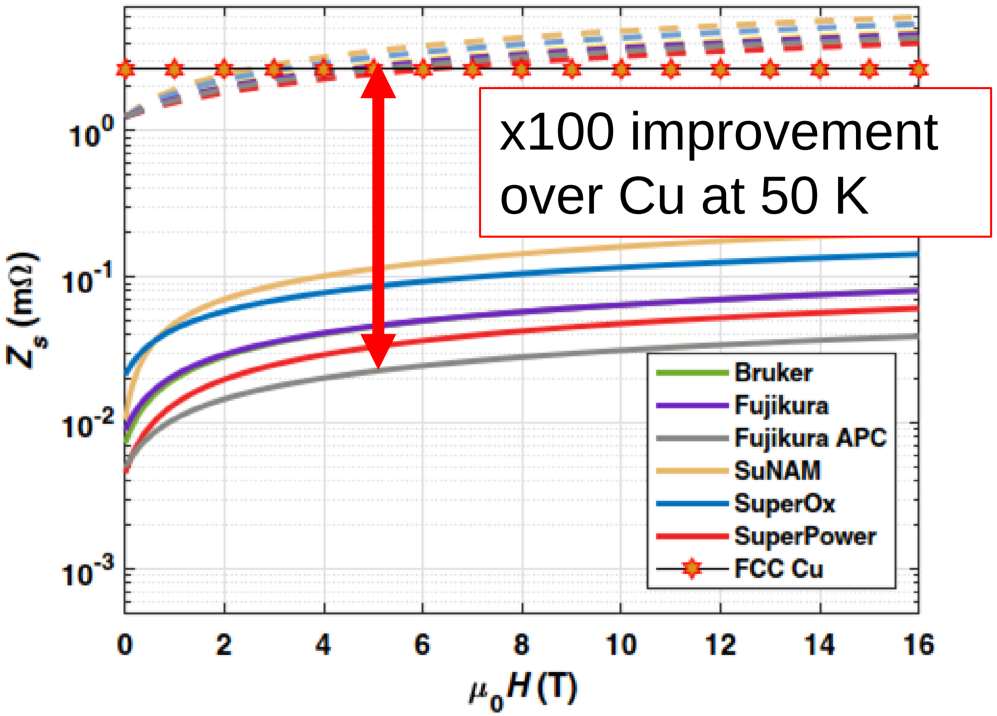
RADES cavity for axion searches

2x improvement of RF quality factor compared to copper
(newer prototype 5x improvement)



Scaling to lower frequency

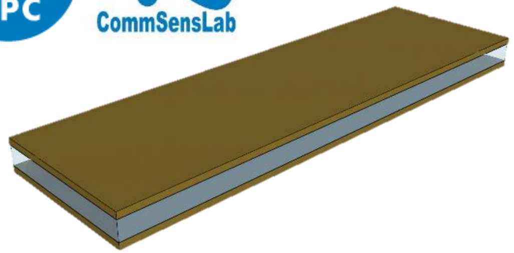
REBCO scaled to 1 GHz at 50 K



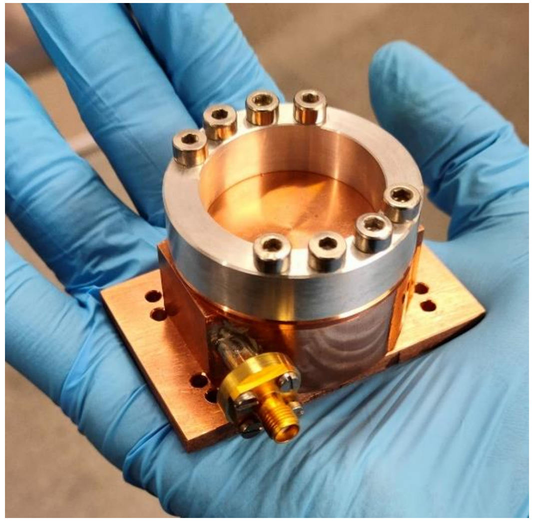
Romanov et al, SciRep 10:12325 (2020)

For HTS Rs scales as f^2
For Cu Rs scales as $f^{1/2}$

A parallel-plate resonator is being commissioned to test samples at ~1 GHz



38x12 mm samples
50 mm bore
16 T
$X_s(T)$ at all frequencies



Will demonstrate real experimental frequency scaling on samples

Outline

- HTS cavities in a strong magnetic field
- HTS cavities at high-gradient
- HTS cavities in both strong field and high-gradient
- Future steps

Potential motivation: linear colliders

- Linear collider studies fall essentially in two categories

Superconducting niobium, CW

Normal conducting copper, pulsed

- Linear collider studies result in roughly similar power consumption for equivalent machines (ie ILC vs CLIC)
- We want to see if HTS in pulsed RF mode allows an optimal gain compared to both Nb and Cu

Cryo-cooled copper -> HTS ?

- The C^3 study aims at cryogenically cooled copper, to attain a larger gradient and save cost in the RF power stations
- A further advantage could come from combining the advantage of higher gradients at lower temperatures, with the higher Q factor of HTS coatings -> **energy efficiency**

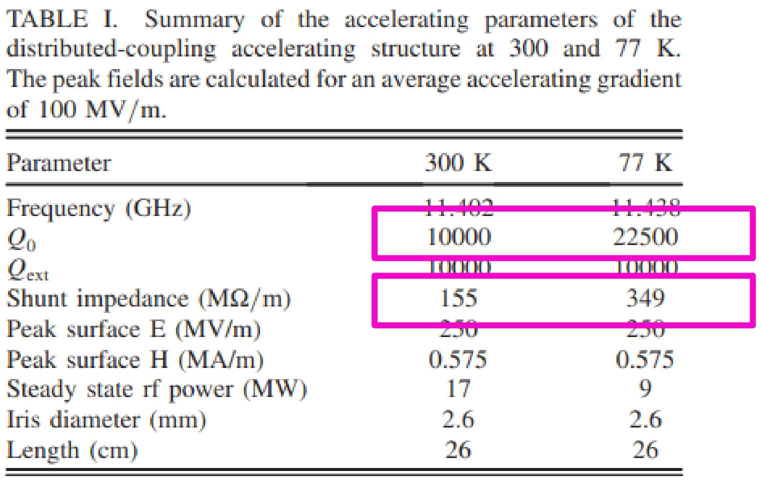


TABLE I. Summary of the accelerating parameters of the distributed-coupling accelerating structure at 300 and 77 K. The peak fields are calculated for an average accelerating gradient of 100 MV/m.

Parameter	300 K	77 K
Frequency (GHz)	11.402	11.438
Q_0	10000	22500
Q_{ext}	10000	10000
Shunt impedance (MΩ/m)	155	349
Peak surface E (MV/m)	250	250
Peak surface H (MA/m)	0.575	0.575
Steady state rf power (MW)	17	9
Iris diameter (mm)	2.6	2.6
Length (cm)	26	26

E. Nanni et al., PRAB 24, 093201 (2021)

Cryoplant efficiency (Carnot + engineering)

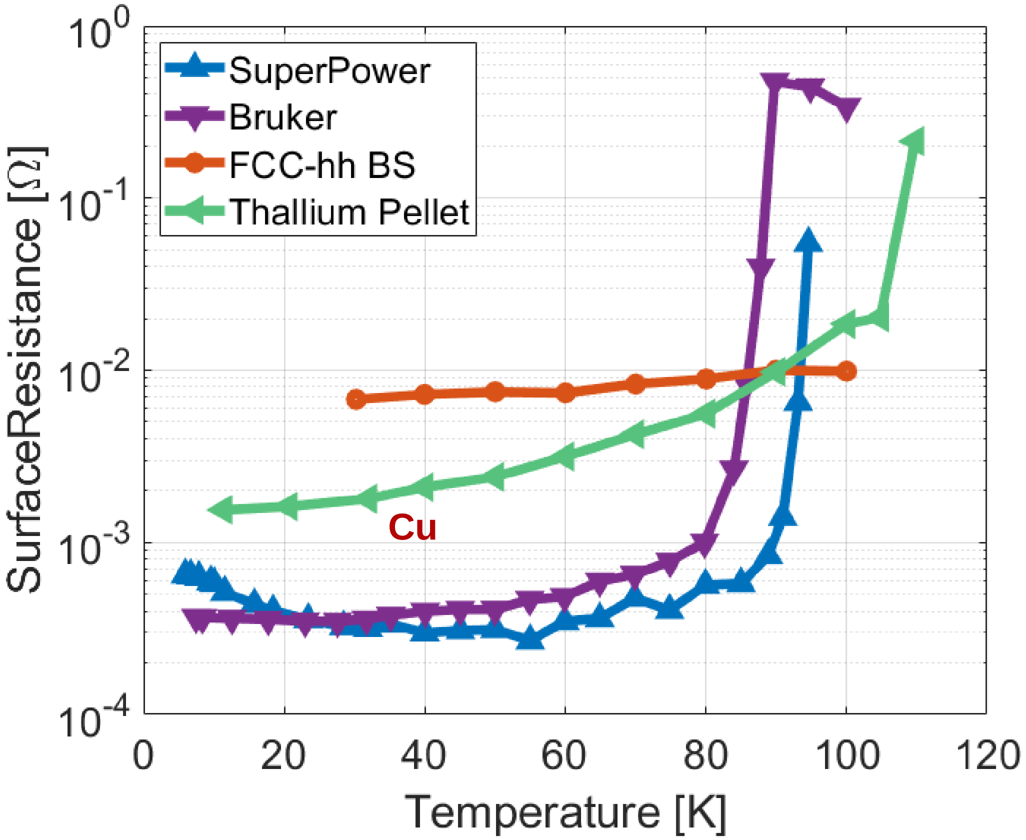
SRF temperature	Ratio W_{300K}/W_{cryo}
77 K	13
50 K	20
4.2 K	230
1.9 K	920

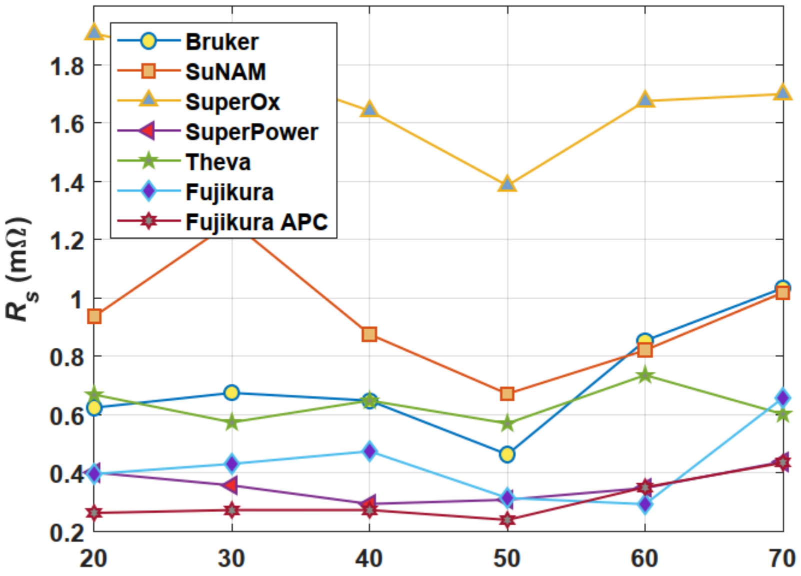
Thanks to T. Koettig, CERN

A factor x10 improvement in Q factor compared to copper could pave the way for significant energy savings

Low-power measurments

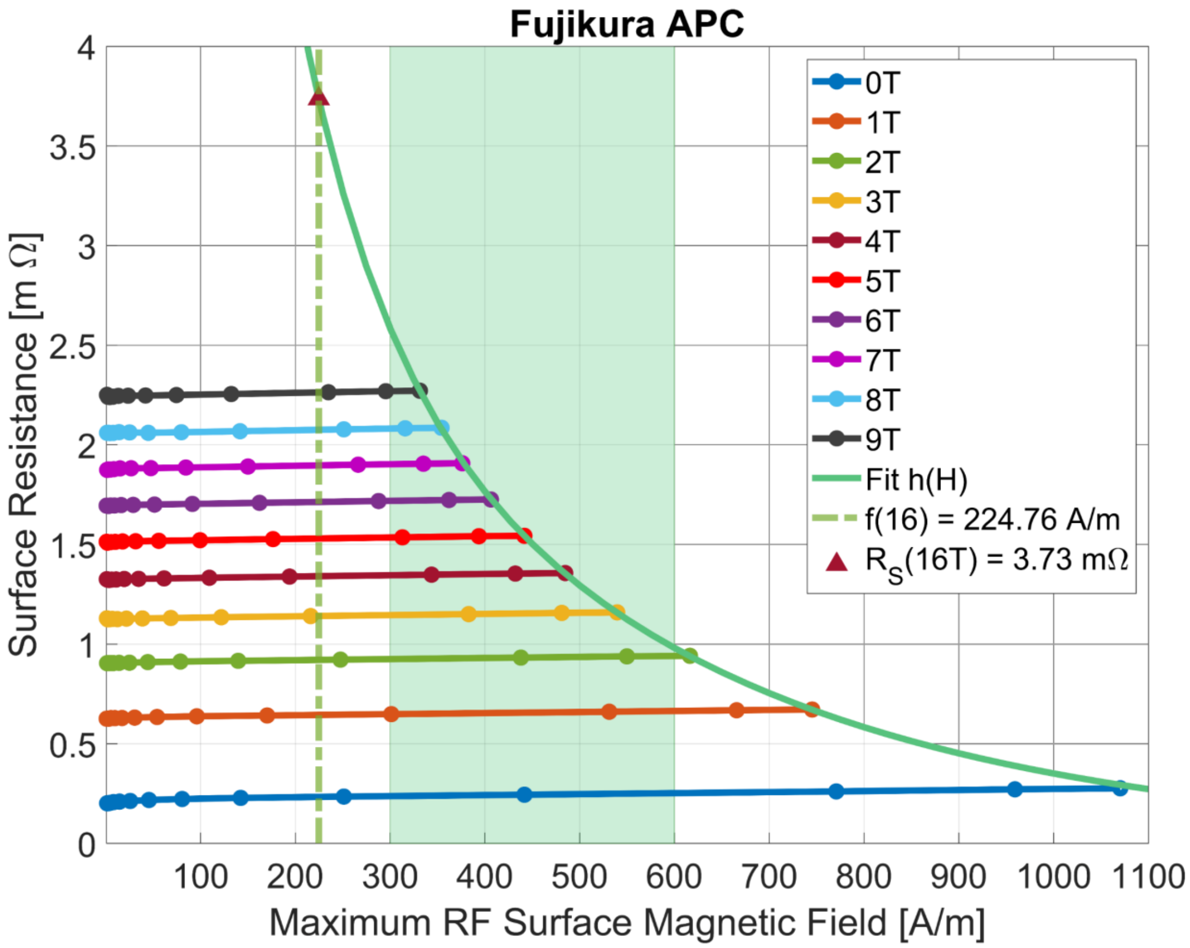
- A potential improvement at least x10 compared to copper (Rs=8mΩ) has been measured on samples of tapes (8 GHz) at low RF power





(adapted from Romanov et al, Sci. Rep. (2020) 10:12325)

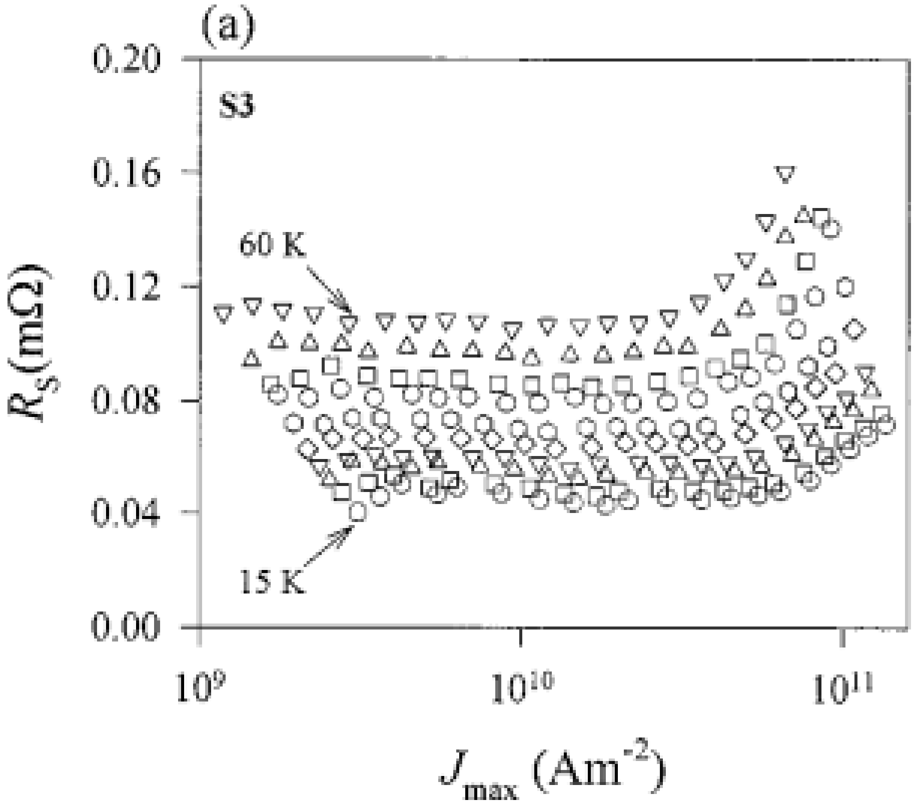
HTS tape at 8 GHz (dielectric resonator)



Patrick Krkotic, PhD dissertation, UPC Barcelona 2022

Literature review - I

- There are very few measurements on HTS at high RF currents (mostly microstrip resonators). But physics is proven.



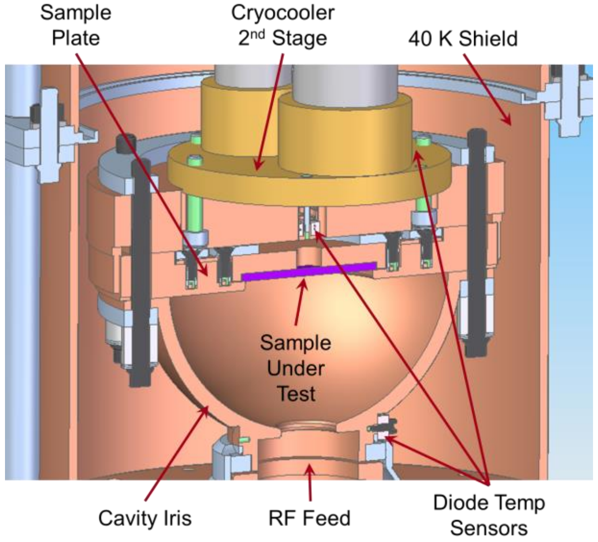
~10^{11} A/m^2 RF current (microstrip resonator, 200 µm, 350 nm thick, 8 GHz)

Powell et al. Journal of Applied Physics 86, 2137 (1999)

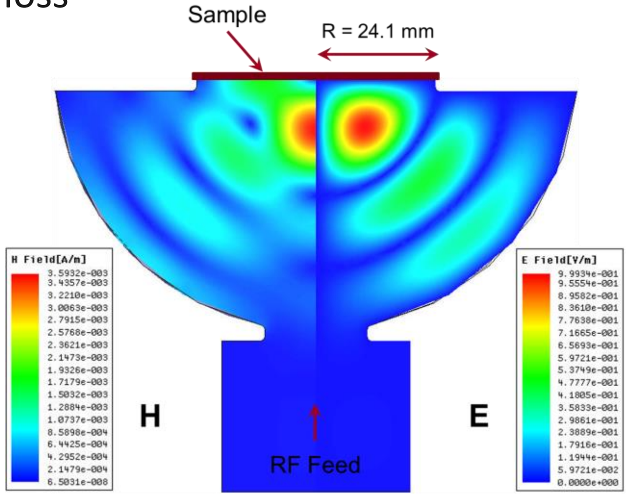
For 1 µm thickness this is equivalent to 10^5 A/m (≅ 0.1 T ≅ 25 MV/m)
in the “high-gradient” range

High-gradient testing at SLAC – supported by I.FAST IIF

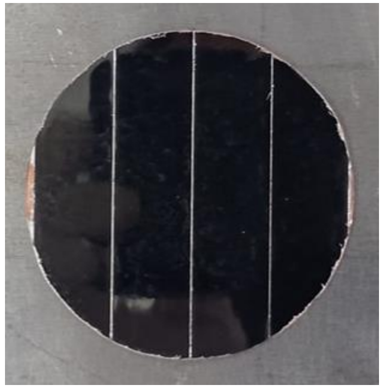
- Demountable high-power RF cavity
- Can achieve H_{peak} of about 360 mT using 50 MW XL-4 Klystron.



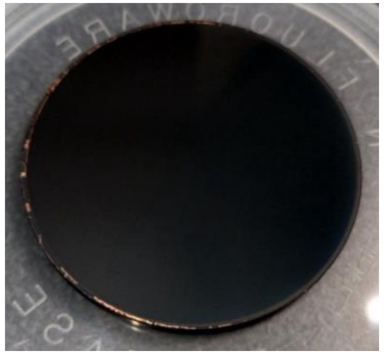
- High-Q X-band hemispheric cavity with a TE_{032}-like mode at 11.4 GHz.
- Zero E-field on the sample
- Maximum H-field on the sample
- Sample accounts for ⅓ of total cavity loss



HTS-coated with tapes
By CSIC-ICMAB



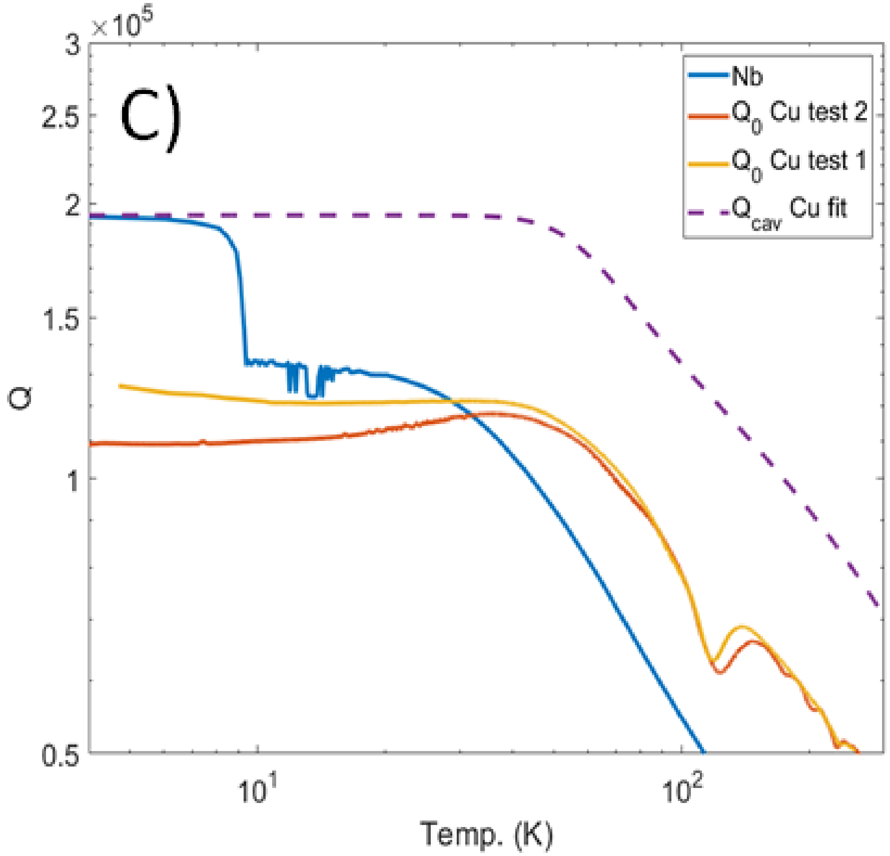
HTS-coated sample
By CERACO



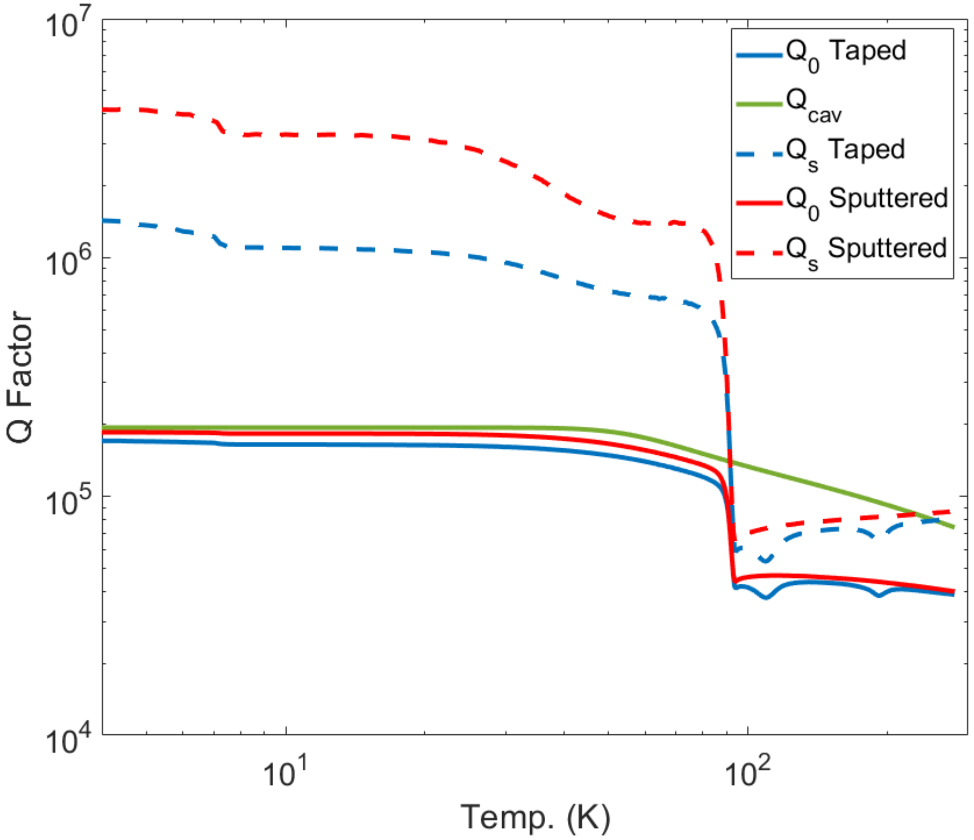
Goal: demonstrate high-gradient pulsed operation of HTS, at cryo-temperatures, and develop large size coatings (50 mm wide tapes)

First results at SLAC

Cu and Nb reference measurements



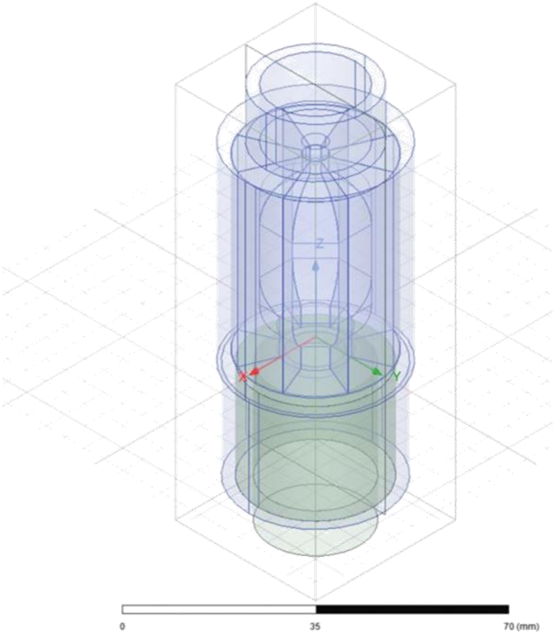
HTS measurements

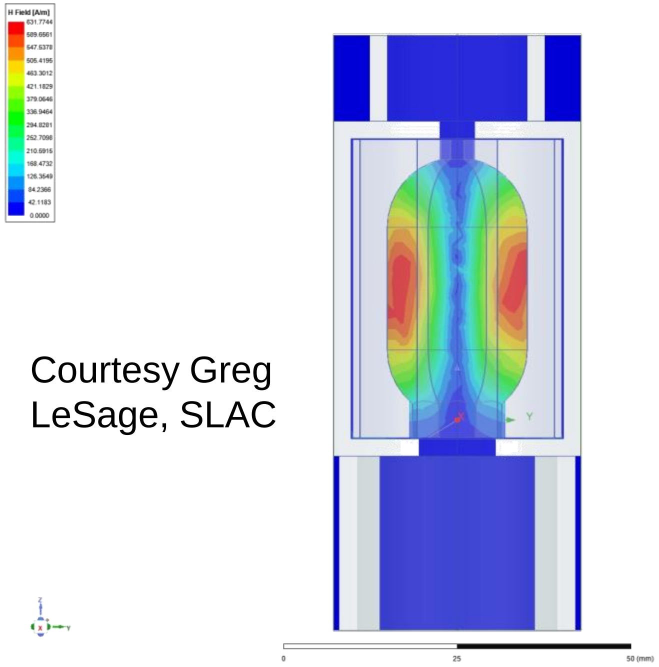


High-gradient tests foreseen shortly

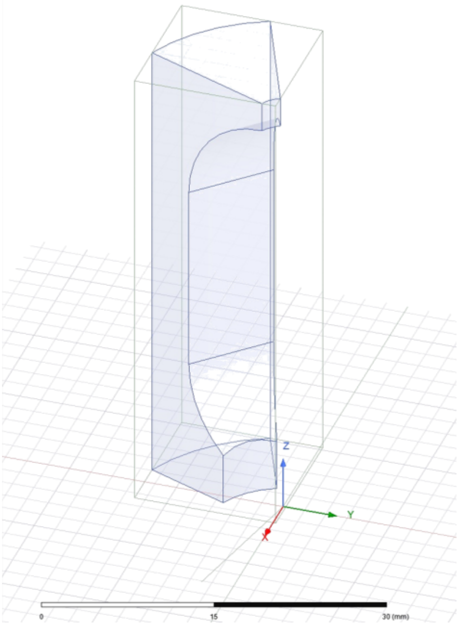
First device validation – supported by I.FAST Innovation Fund

- Device approach: X-band pulse compressor (SLAC) as first “real” device
- Coated with small tapes by CSIC-ICMAB for device validation
- Future goal: full device with large-size tapes (or directly coated on copper, ideally)





Courtesy Greg LeSage, SLAC



Max surface field 3.126 MA/m

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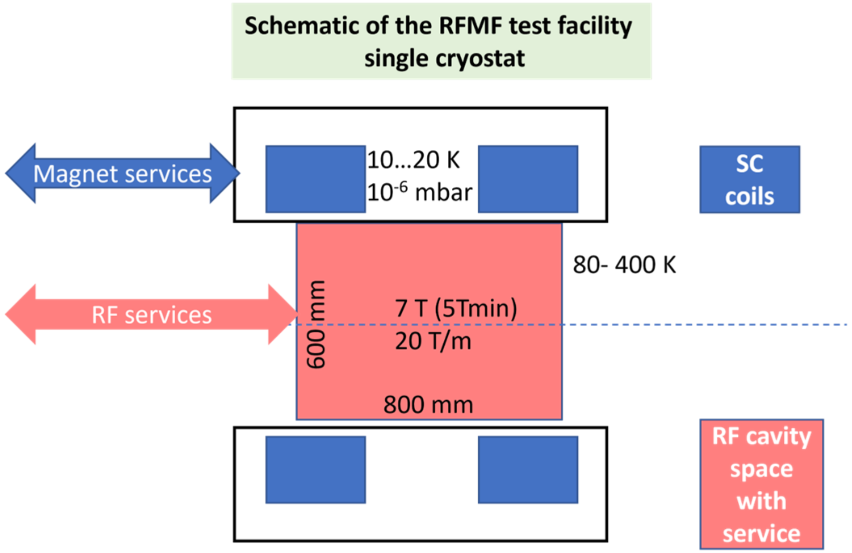
Possible test in a dedicated RF stand

- See talk of Dario Giove later today



Schematic of the RFMF test facility single cryostat

Magnet services

10…20 K

10^{-6} mbar

SC coils

80- 400 K

RF services

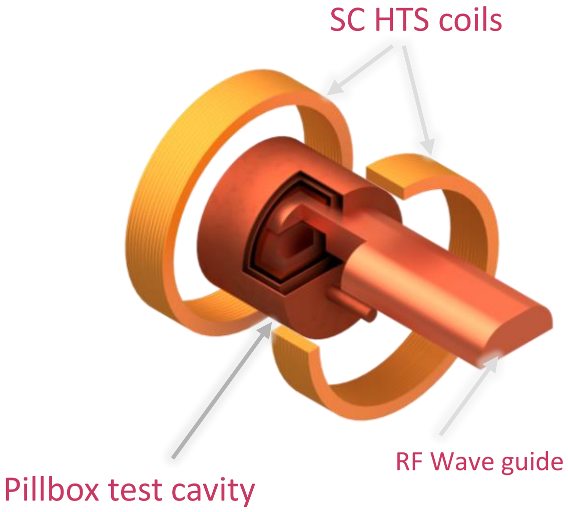
600 mm

7 T (5Tmin)

20 T/m

800 mm

RF cavity space with service



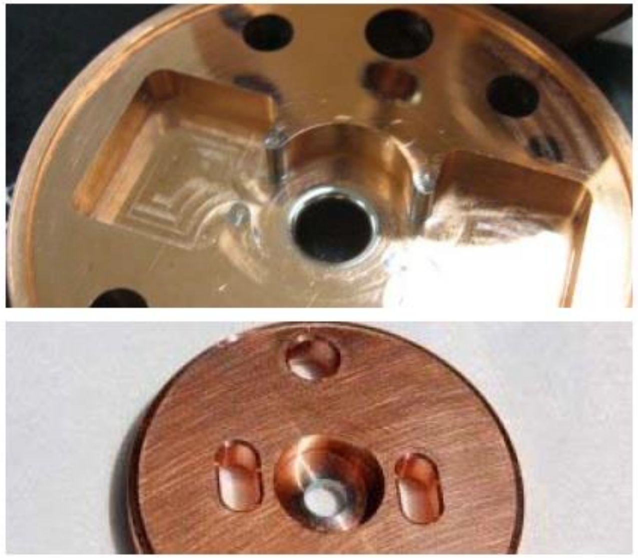
Sc magnet/cryostat sketch by M. Castoldi & Stefano Sorti, UMIL & INFN-LASA

(RF drawing by Guillaume Ferrand –CEA)

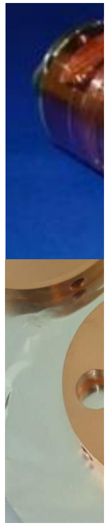
- Availability of a high-field / high-gradient test stand foreseen within the MuCol study could be beneficial for the entire HTS-HFF community

Possible practical implementation of HTS tape-coated cavities

- How could a future cavity look like? Bimetallic cavities



J. Haimson, WEPMS085,
PAC07 (s.steel inserts)



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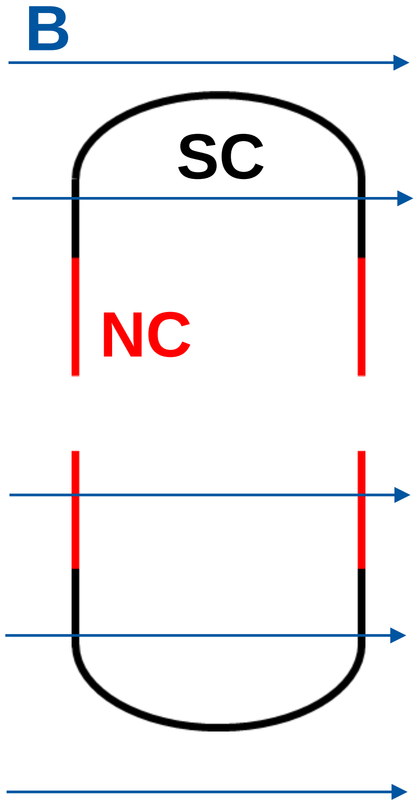
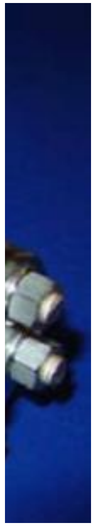
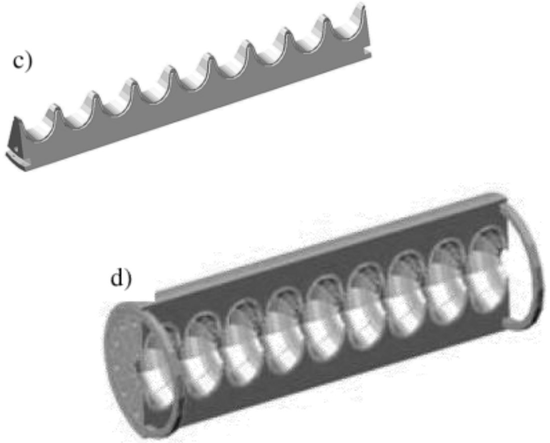






P. McIntyre et al., IEEE
TAS 19 (2009) 1380

Composite cavities exist and have ed.

Joints at low-current regions are standard practice even in SRF cavities (ie QWRs)

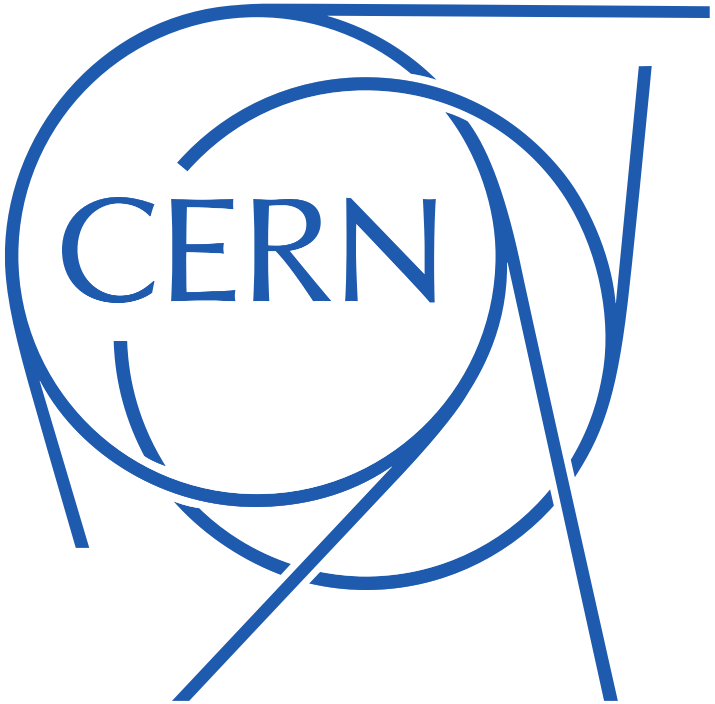
Segmentation at zero-current region is possible, see device being designed at SLAC

Final remarks

- No data for HTS at high-gradient and in strong magnetic field exist (either samples or cavities): experiments needed

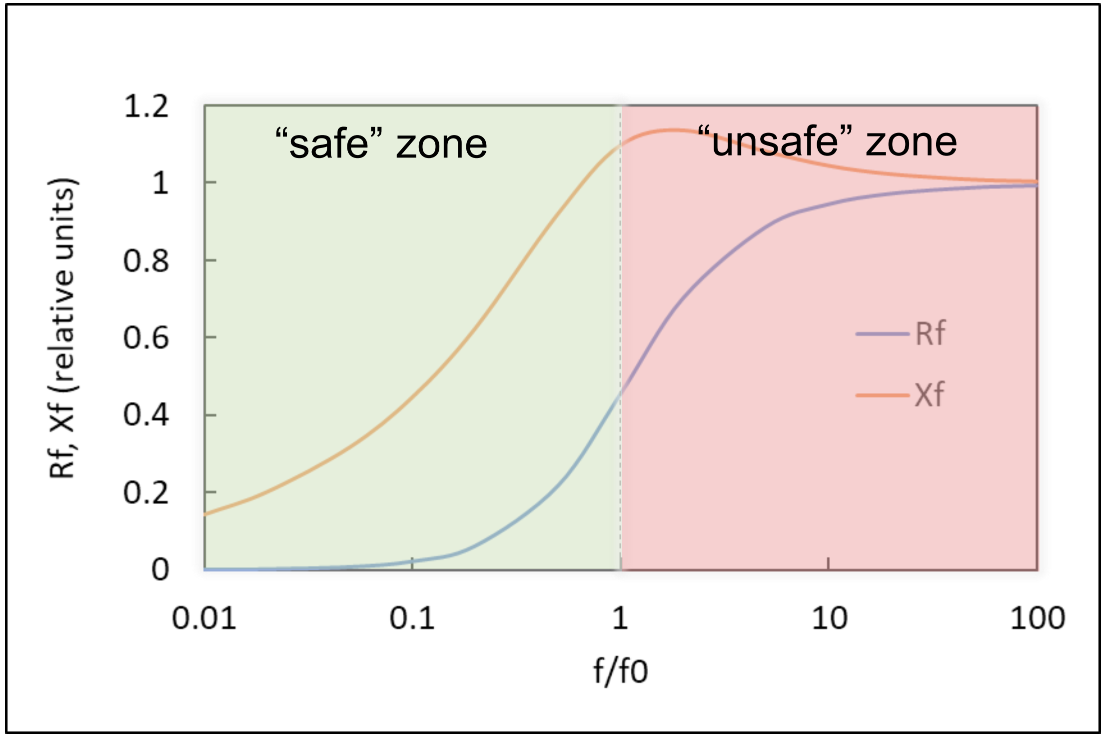
- Overall energy efficiency would have to be studied, taking into account: operating temperature, cryo-efficiency, possible Q-factor, pulsed operation

- Fabrication technologies for real cavities have to be assessed: wider soldered tapes, or develop a direct HTS coating technique?


CERN

Effect of magnetic field: fluxon losses in RF

Surface resistance, reactance due to vortex motion



Case $f < f_o$

$$R_f = \frac{\rho_n}{2\lambda}\frac{B_o}{B_{c2}}\frac{f^2}{f_0^2} \qquad B_0 \,\square\, B_{c2}$$

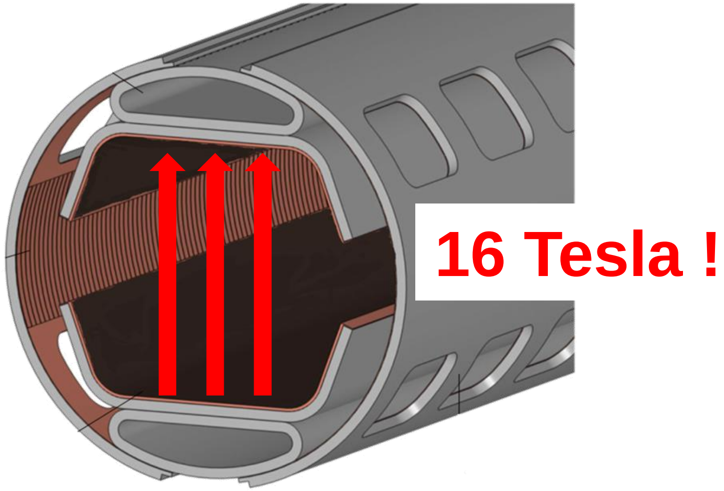
$$R_f = \frac{R_n}{\sqrt{2}}\sqrt{\frac{B_o}{B_{c2}}}\left(\frac{f}{f_0}\right)^{3/2} \qquad B_0 \,\square\, B_{c2}$$

$$f_o(B_o) = \frac{\omega_o(B_o)}{2\pi} = \frac{\rho_n\sqrt{B_o}\,J_c(B_o)}{\sqrt{\varphi_o}\,B_{c2}}$$

To maximize f_0 and minimize fluxon losses we need high J_c materials

HTS for the FCC-hh beam screen

- Recent work motivated by the need of HTS materials for replacing copper in the FCC-hh beam screen, to reduce beam coupling impedance.
- Beam produces RF fields
- Extremely challenging requirements:
  - HTS must operate at 50 K and 16 T
  - Critical fields Hc_2 , H_{irr} >> 16T
  - $J_c > 25$ kA/cm^2 ($2.5\text{x}10^8$ A/m^2)
  - Surface resistance R_s better than for copper
- Compatible with accelerator environment
  - Minimize dipole field distortion due to persistent currents (Note 1)
  - UHV compatible, low SEY, lifecycle assessment, etc..



Calatroni, IEEE TAS 26, 3500204 (2016)
Calatroni et al, SuST 30, 075002 (2017)

How to make it in practice ?

Manufacture the screen using REBCO tapes soldered to the screen

Coat the inside of the screen with Tl-1223 films

ICMAB
INSTITUT DE CIÈNCIA DE MATERIALS DE BARCELONA
EXCELENCIA SEVERO OCHOA
CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

ALBA

IFAE
Institut de Física d'Altes Energies
EXCELENCIA SEVERO OCHOA
BIST Barcelona Institute of Science and Technology

UPC
CommSensLab
EXCELENCIA MARÍA DE MAEZTU 2017 - 2020

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ATOMINSTITUT

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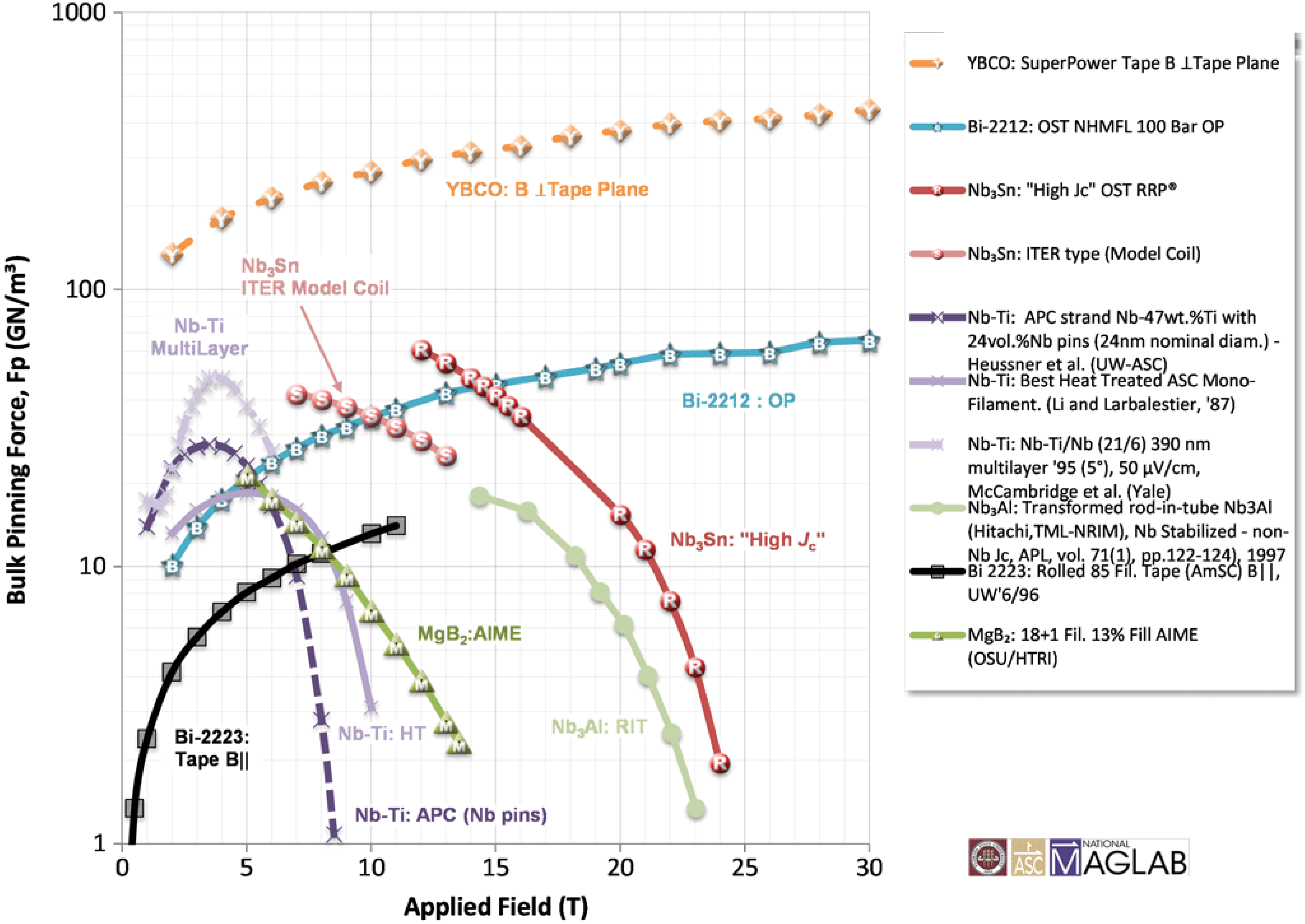
UNIVERSITÀ DEGLI STUDI

Zoo of superconductors

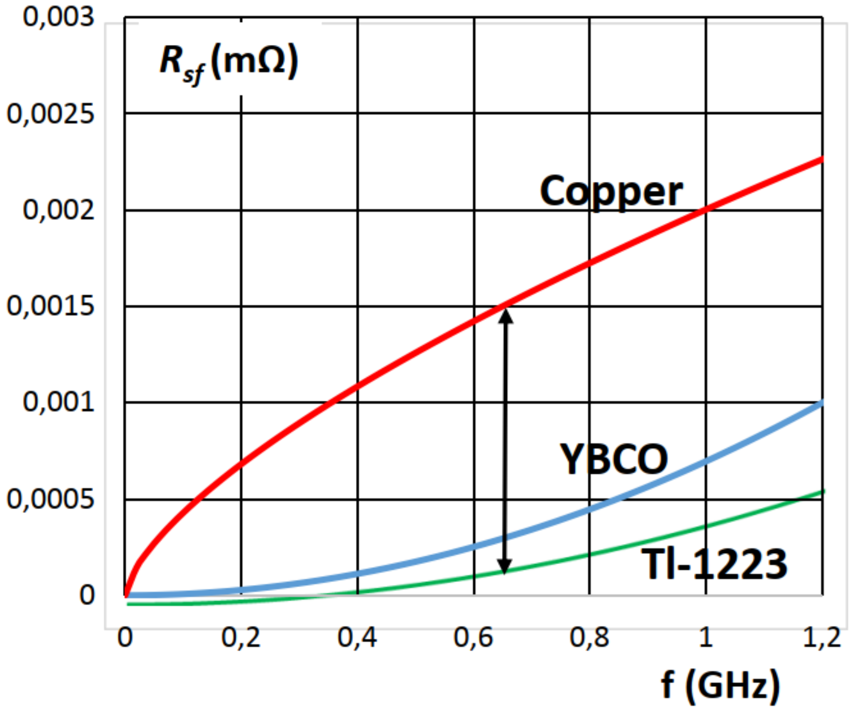
Pinning force

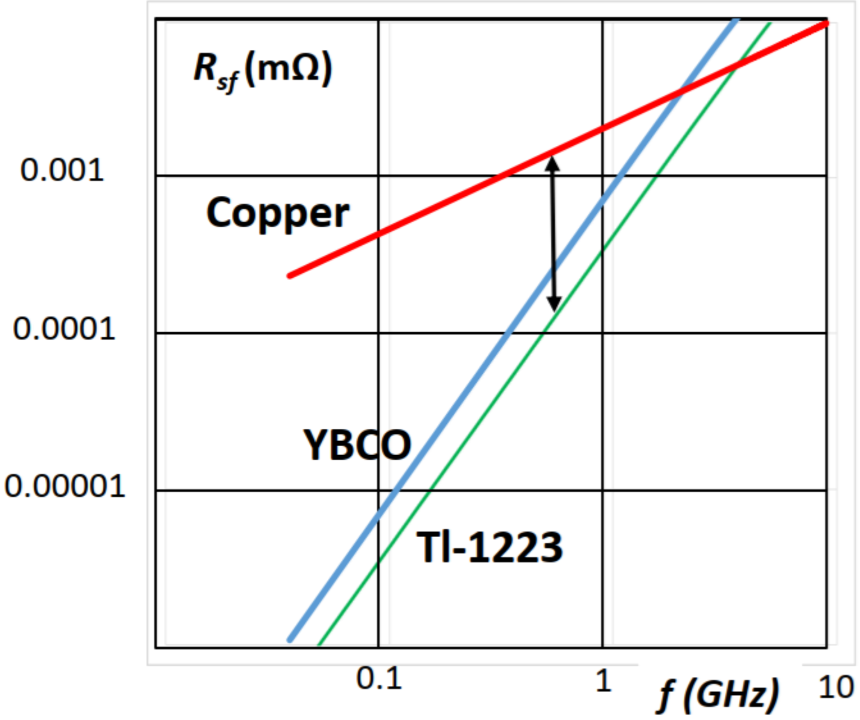


https://nationalmaglab.org/magnet-development/applied-superconductivity-center/plots

Predicted surface resistance of HTS in 16 T field

YBCO	T_c=92K	T=50K	B_0=16T	$J_c(50,16)=7.5\times10^{9}Am^{-2}$	$B_{c2}(50)$=40T	$\rho_n=60\mu\Omega cm$	f_0=10GHz
Tl-1223	T_c=125K	T=50K	B_0=16T	$J_c(50,16)=1\times10^{10}Am^{-2}$	$B_{c2}(50)$=80T	$\rho_n=80\mu\Omega cm$	f_0=14GHz

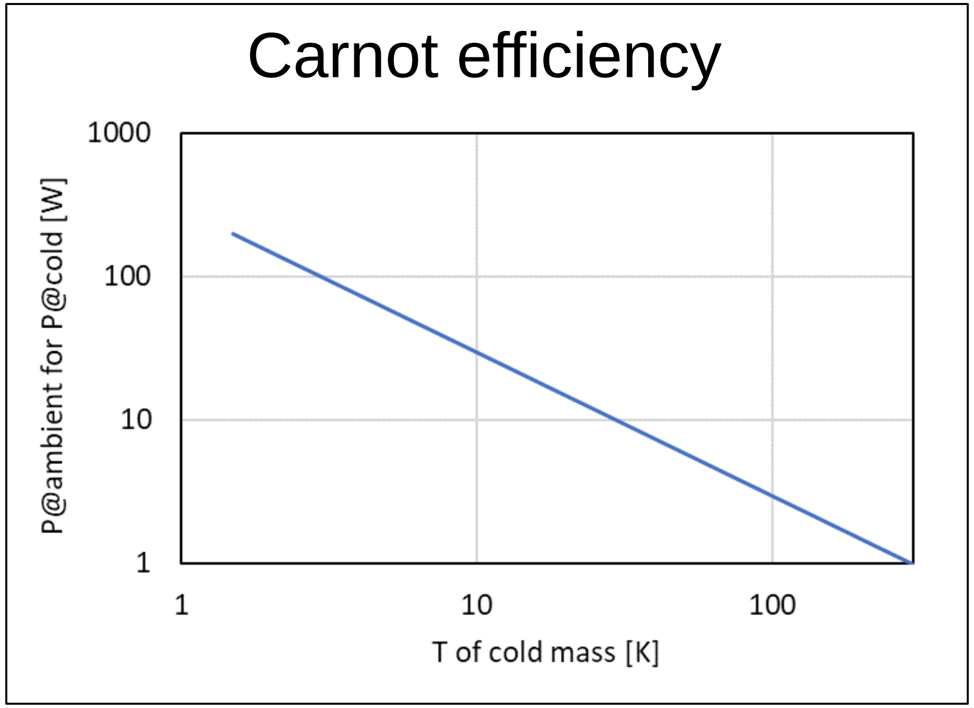


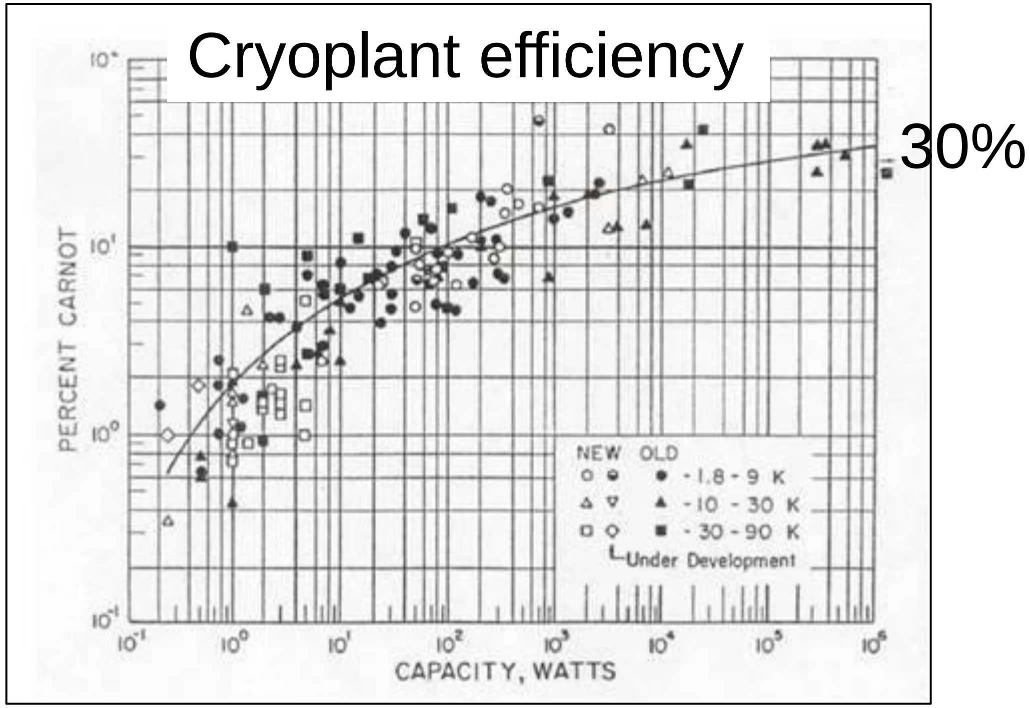


For HTS the Rs scales as f^2

For Cu the Rs scales as $f^{1/2}$

Cryogenic losses: SRF aimed at energy saving compared to NRF


Carnot efficiency


Cryoplant efficiency

30%

Power consumption for 1 W @ 77 K	13 W
Power consumption for 1 W @ 20 K	50 W
Power consumption for 1 W @ 4.2 K	230 W
Power consumption for 1 W @ 1.9 K	920 W

Thanks to T. Koettig, CERN

Test of Nb3Sn films up to 12 T

IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 29, NO. 5, AUGUST 2019 3500104

Surface Impedance Measurements on Nb_3Sn in High Magnetic Fields

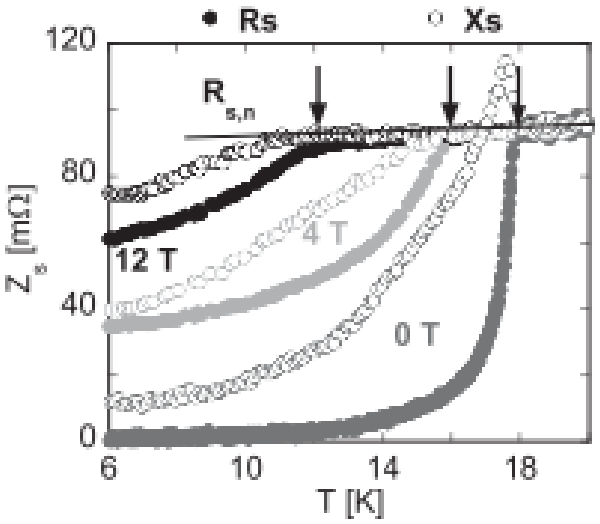


Fig. 2. Z_s measured at fixed $\mu_0 H$, depicted in the figure, and varying T. Full circles: R_s; empty circles: X_s. Colors: black, $\mu_0 H = 12$ T; light gray, $\mu_0 H = 4$ T; dark gray, $\mu_0 H = 0$ T. Vertical arrows indicate $T_{c2}(H)$.

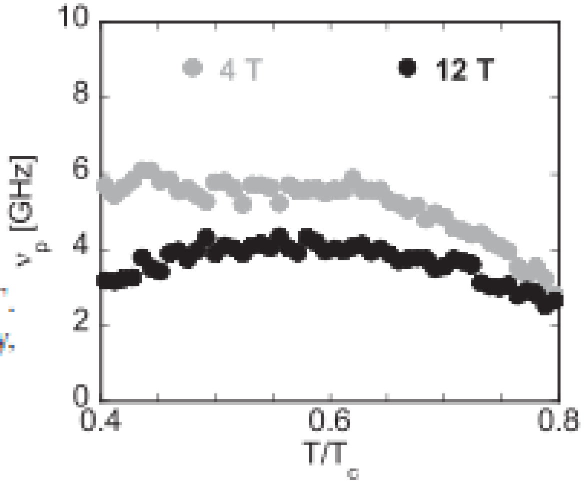
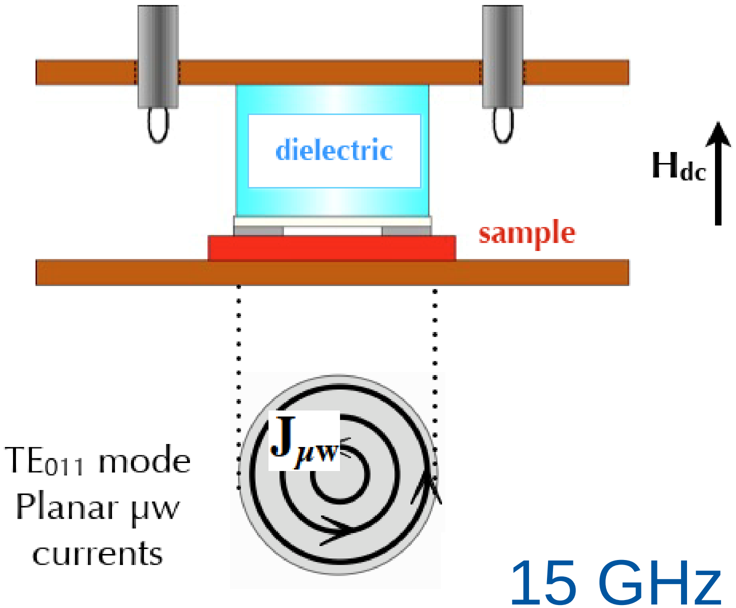
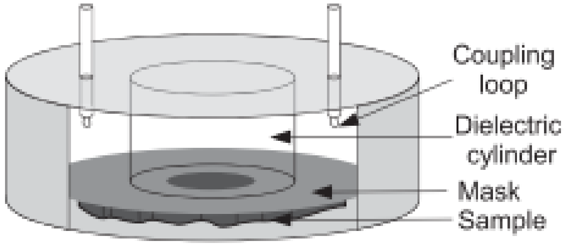


Fig. 4. The depinning frequency ν_p at $\mu_0 H = 12$ T (black points) and at $\mu_0 H = 4$ T (gray points). The ν_p is almost constant up to 0.65 T_c.

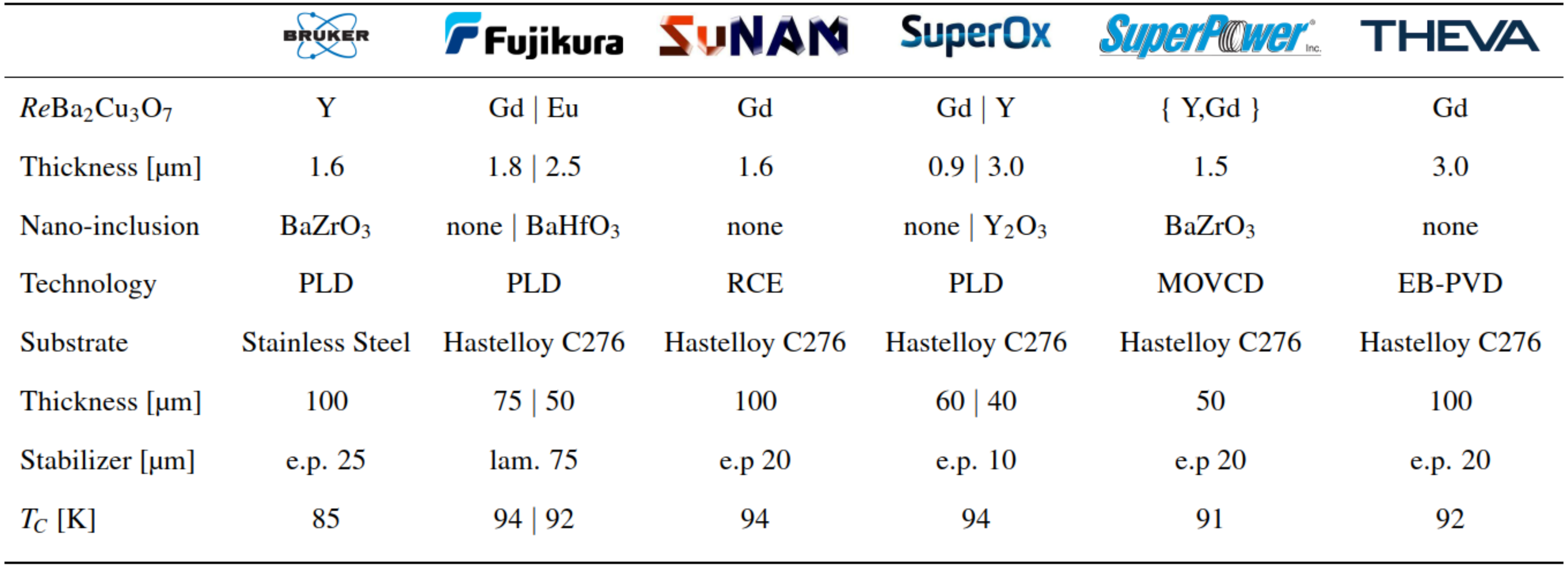


TE_{011} mode
Planar μw
currents

15 GHz



HTS coating technologies



	BRUKER	Fujikura	SuNAM	SuperOx	SuperPower Inc.	THEVA
$Re\text{Ba}_2\text{Cu}_3\text{O}_7$	Y	Gd | Eu	Gd	Gd | Y	{ Y,Gd }	Gd
Thickness [µm]	1.6	1.8 | 2.5	1.6	0.9 | 3.0	1.5	3.0
Nano-inclusion	$BaZrO_3$	none | $BaHfO_3$	none	none | Y_2O_3	$BaZrO_3$	none
Technology	PLD	PLD	RCE	PLD	MOVCD	EB-PVD
Substrate	Stainless Steel	Hastelloy C276	Hastelloy C276	Hastelloy C276	Hastelloy C276	Hastelloy C276
Thickness [µm]	100	75 | 50	100	60 | 40	50	100
Stabilizer [µm]	e.p. 25	lam. 75	e.p 20	e.p. 10	e.p 20	e.p. 20
T_C [K]	85	94 | 92	94	94	91	92

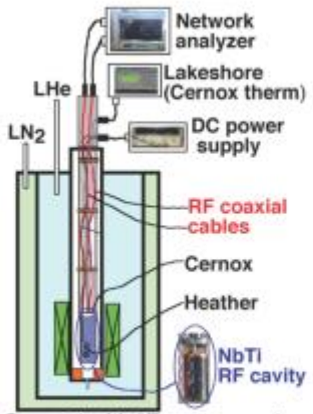
Patrick Krkotic, PhD dissertation, UPC Barcelona 2022

INFN: NbTi and NbTiN cavities for axion searches

IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 29, NO. 5, AUGUST 2019 3500605

Microwave Losses in a DC Magnetic Field in Superconducting Cavities for Axion Studies

RF cavity
2 Cu semi-cells+NbTi film



Cryostat with 8T sup. magnet

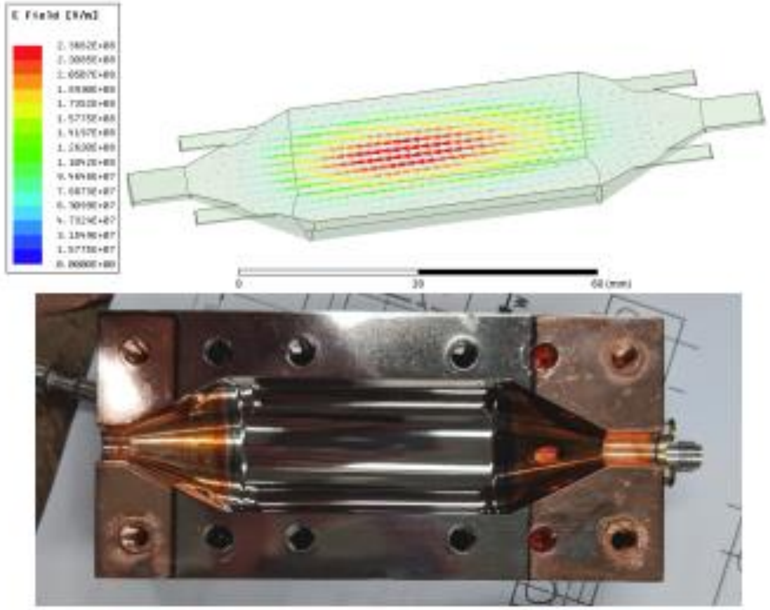
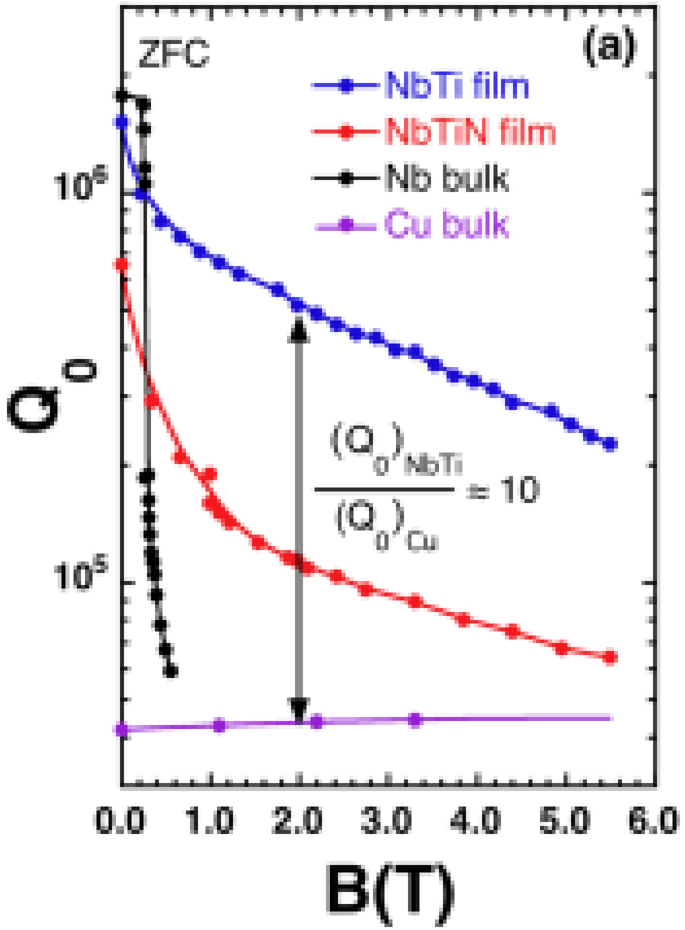


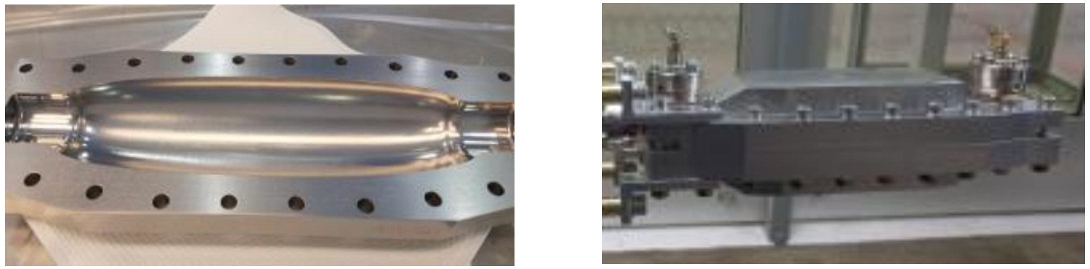
FIG. 1: The upper image represents the electric field of 9.08 GHz TM010 mode in arbitary amplitude units, while the lower photo is one of the two halves of the superconducting cavity.



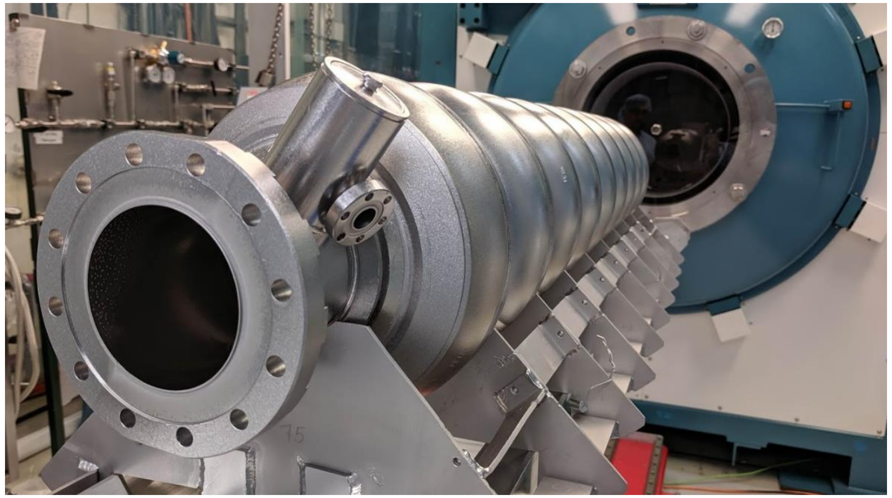
x10 improvement over copper at 4.2 K

Nb_3Sn @ 3.9 GHz in strong magnetic field: FNAL results

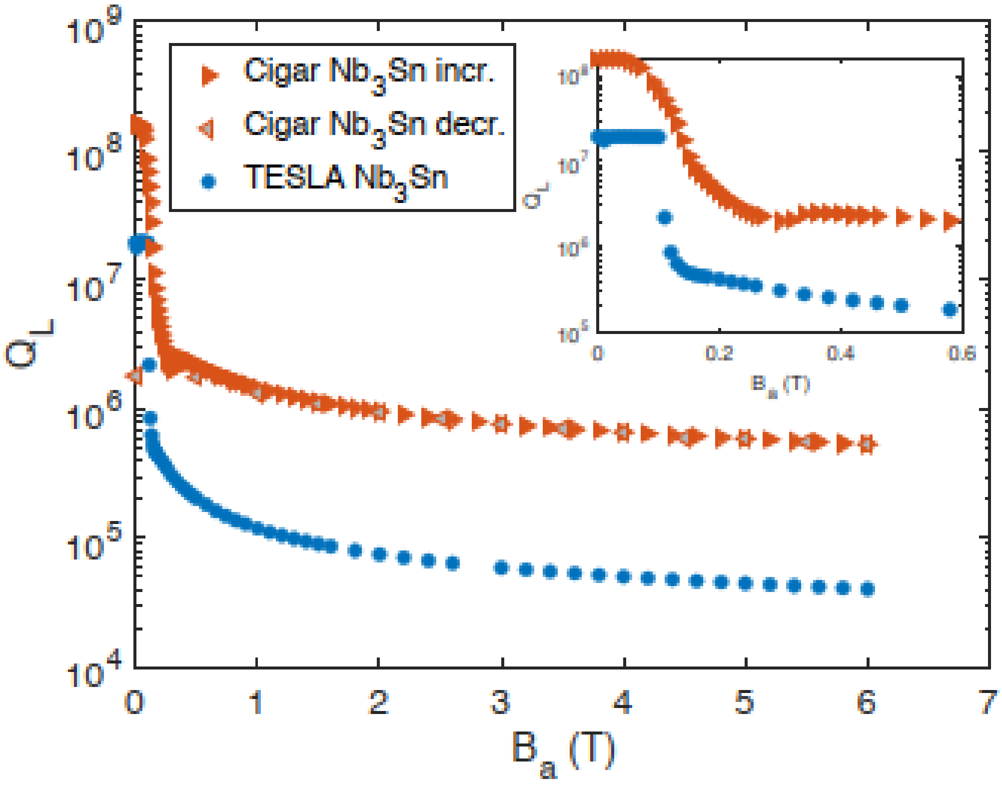
Cigar-shaped cavity 3.9 GHz



1-cell ILC type 3.9 GHz



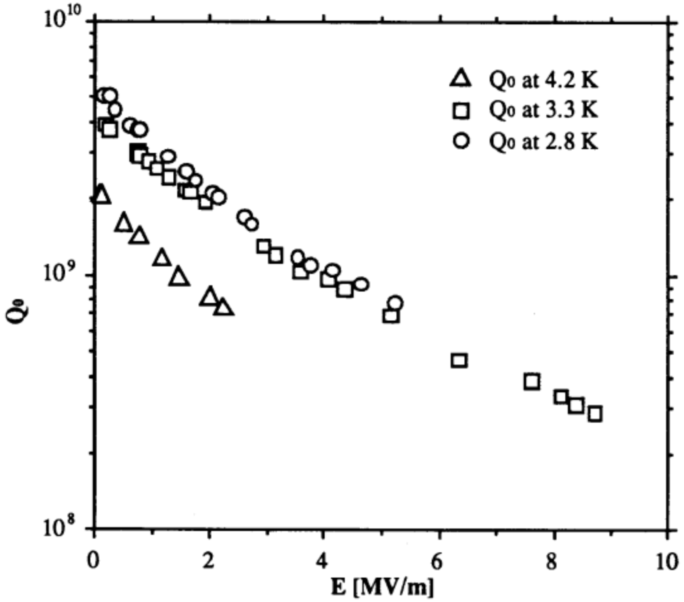
S. Posen et al. ArXiv 2201.10733



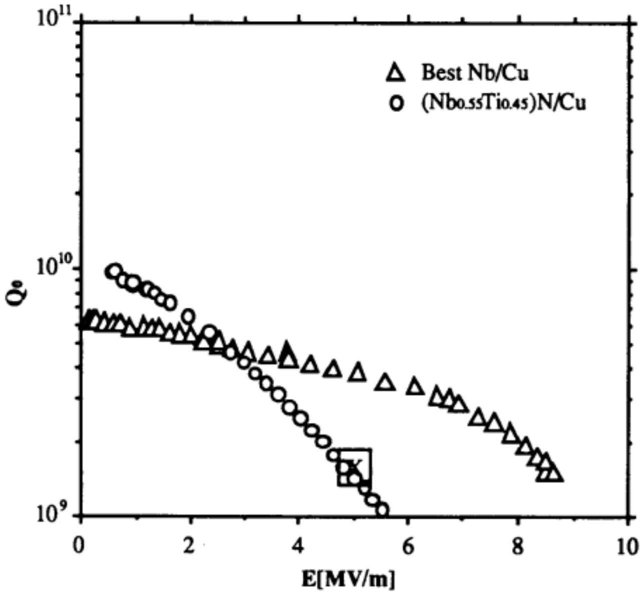
Ideally, Nb_3Sn from vapor tin diffusion should then be compared to Nb_3Sn from sputtering

NbTi / NbTiN and Nb_3Sn at high RF field

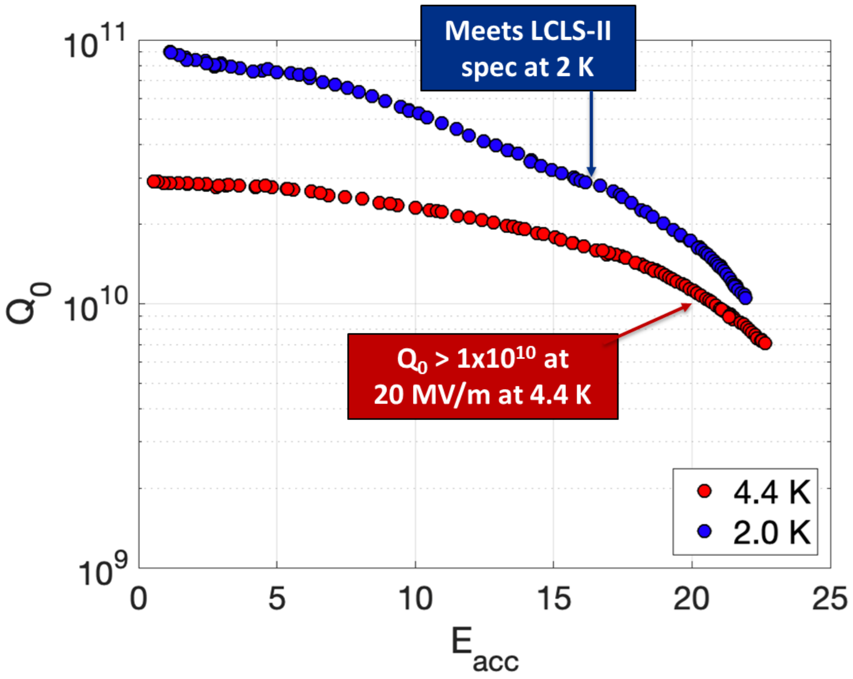
NbTi 500 MHz



NbTiN 500 MHz, 4.2 K



S. Calatroni et al., Proc of the SRF 91



Meets LCLS-II spec at 2 K

$Q_0 > 1x10^{10}$ at 20 MV/m at 4.4 K

S. Posen – FNAL (TTC 2019 talk)